Sound

Week 14, Lesson 1

- **The Origin of Sound**
- **Sound Waves in Air**
- **Equations for Sound Speed**
- **Speed of Sound in Air**
- **Intensity, Loudness**
- **Beats, Doppler Effect**

References/Reading Preparation:
Schaum’s Outline Ch. 23
Principles of Physics by Beuche – Ch.15

The Origin of Sound

Sound waves are longitudinal waves that are transmitted through almost any substance – solid, liquid, or gas.

The waves are created by any mechanism which produces compressional vibrations of the surrounding medium.

Some examples:
- vibrating string of a guitar
- vibrating vocal chords
- exploding gas in a firecracker

Sound cannot travel through a vacuum because in a vacuum there is no material to transmit the compressions.

We are most often concerned with sound waves in air since that is the basis of our sense of hearing.

However, sound travels faster and with less energy loss in liquids and solids than in air.

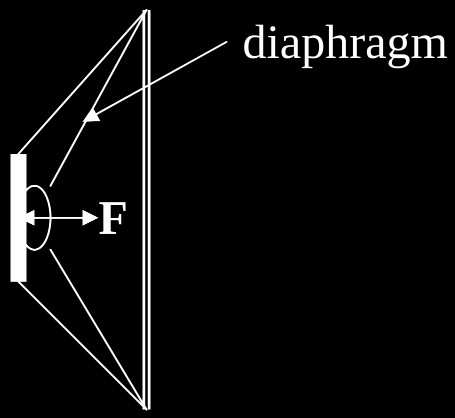
Although we usually refer to sound as those waves we can hear, sound can have frequencies far above and far below those to which our ears are sensitive.

Sound Waves in Air

Let us now consider the action of a loudspeaker generating a simple sound.

A simple loudspeaker consists of a cone-shaped sheet of flexible material, called a diaphragm, that can be oscillated back and forth by means of an applied force **F**.

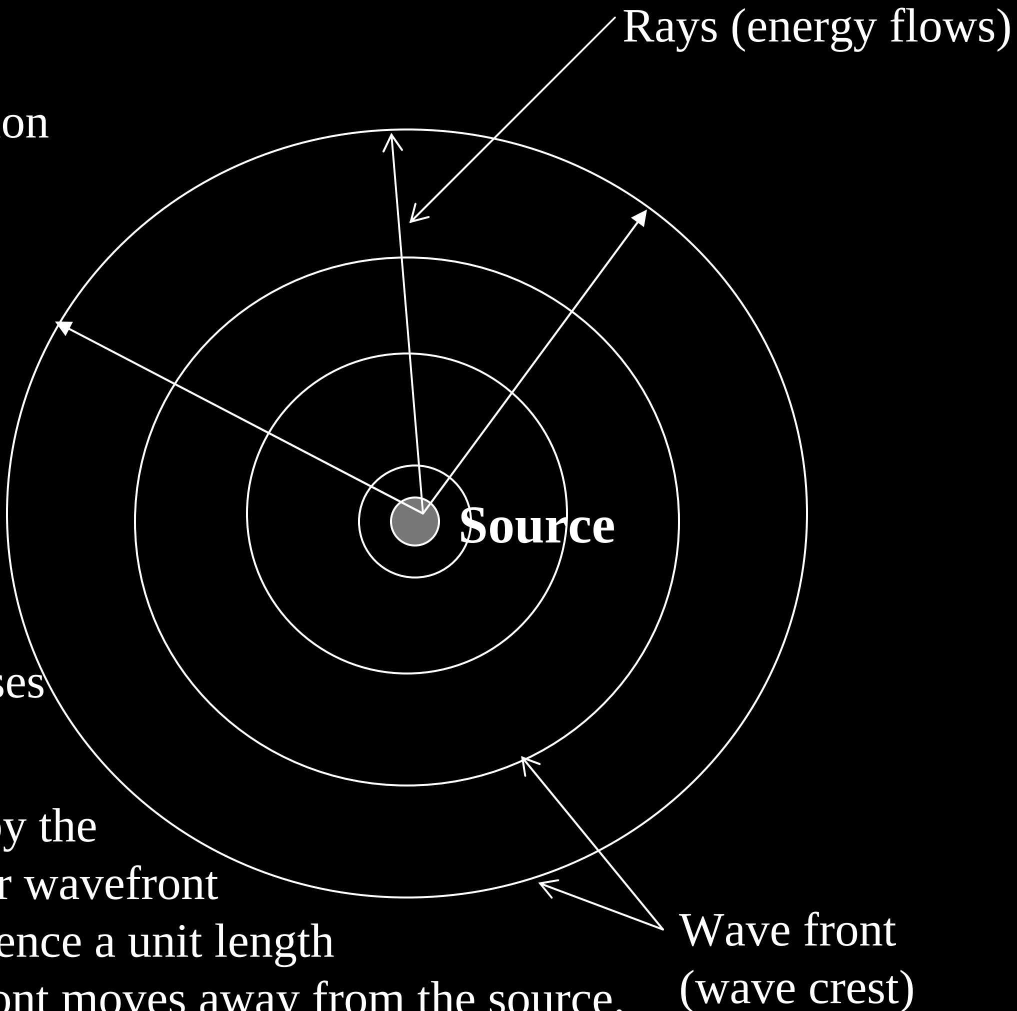
When the diaphragm moves to the right, it compresses the air in front of it and a **compression** travels out through the air.



An instant later, the diaphragm is moving to the left, leaving a region of decreased air pressure in its wake called a **rarefaction**.

Hence, a series of pressure disturbances, the compressions and rarefactions, travel out from the speaker.

The sound waves sent out by a loudspeaker or any other sound source are not usually confined to a straight line path. Instead, they spread out in all directions from the source.



Because this is a three-dimensional situation the wave fronts are **spherical** surfaces centred on the sound source.

These spherical waves have decreasing curvature as they move further away from the source and appear essentially flat at a distant point – the waves are essentially flat planes.

With these waves, their amplitude decreases with increasing distance from the source.

This reflects the fact that the energy carried by the wave is spread out over an increasingly larger wavefront as the wave proceeds out from the source. Hence a unit length of a wave front contains less energy as the front moves away from the source.

Hearing

When the compressions and rarefactions of the waves strike the eardrum, they result in the sensation of sound – provided the frequency of the waves is between about 20 Hz and 20,000 Hz.

Waves with frequencies above 20 kHz are called ***ultrasonic*** waves.

Waves with frequencies below 20Hz are called ***infrasonic*** waves.

The Speed of Sound

In an ideal gas of molecular mass M and absolute temperature T, the speed of sound v is given by:

$$v = \sqrt{\frac{\gamma RT}{M}} \quad \text{(ideal gas)}$$

where

R = the gas constant
γ= the ratio of specific heats c_p/c_v
γ = 1.67 for monatomic gases (He, Ne, Ar),
and 1.40 for diatomic gases (N_2, O_2, H_2)

The speed of compressional waves in other materials is given by:

$$\boxed{v = \sqrt{\frac{\text{modulus}}{\text{density}}}}$$

If the material is in the form of a bar, Young's modulus is used.

For liquids, one must use the bulk modulus.

Worked example

Find the speed of sound in neon gas at 0°C. M = 20.18 kg/kmol·K and R = *8314* kg/kmol

(ans. 432 m/s)

Worked example

What is the speed of sound waves in water? The bulk modulus for water is 2.2×10^9 N/m^2.

(ans. 1.48 km/s)

The Speed of Sound in Air

The speed of sound in air at 0°C is 331 m/s.

The speed increases with temperature by about 0.61 m/s for each °C rise.

Sound speeds v_1 and v_2 at absolute temperatures T_1 and T_2 are related by

$$\boxed{\frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}}}$$

The speed of sound is essentially independent of pressure, frequency and wavelength.

Worked example

An explosion occurs at a distance of 6.0 km from a person. How long after the explosion does the person hear it? Assume the temperature is 14°C.

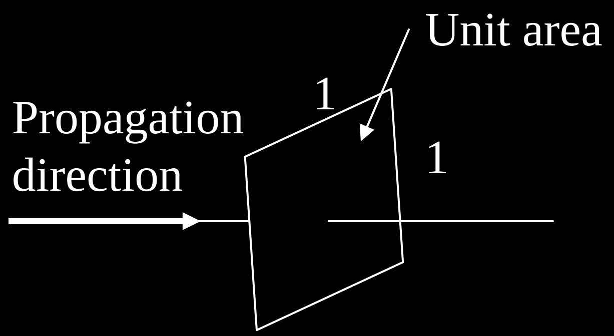
(ans. 17.6 s)

Intensity and Intensity Level

The intensity *I* of a wave is defined in terms of the energy it carries.

We consider a unit area perpendicular to the propagation direction, as shown.

We define the intensity of the wave to be the energy the wave carries per second through this unit area.



Since power is energy produced per unit of time,

> **Sound Intensity** *I* is the power passing through a unit area perpendicular to the direction of wave propagation.
>
> $$I = \text{power/area}$$

For a sound wave with amplitude a_o and frequency f, traveling with a speed v in a material of density ρ,

$$\boxed{I = 2\pi^2 f^2 \rho v a_o^2}$$

where

f is in Hz
ρ is in kg/m^3
v is in m/s
a_o is in m
I is in W/m^2

Loudness

Loudness is a measure of the human perception of sound.

Although a sound of high intensity is perceived as louder than a wave with lower intensity, the relation is far from being linear.

The sensation of sound is roughly proportional to the logarithm of the sound intensity.

Intensity level (or **sound level**) is defined by an arbitrary scale that corresponds roughly to the sensation of loudness.

The zero on this scale is taken at the sound-wave intensity $I_o = 1 \times 10^{-12}$ W/m^2, which corresponds roughly to the weakest audible sound.

The scale is defined by:

$$\boxed{\text{Intensity level of } I \text{ in decibels} = 10 \log(I/I_0)}$$

The ***decibel*** (dB) is a dimensionless unit.

The following table shows approximate sound intensities and intensity levels.

Type of sound	Intensity (W/m^2)	Intensity Level (dB)
Pain producing	1	120
Jackhammer or riveter*	10^{-2}	100
	10^{-3}	90
	10^{-4}	80
Busy street traffic*	10^{-5}	70
Ordinary conversation*	10^{-6}	60
	10^{-7}	50
	10^{-8}	40
	10^{-9}	30
Average whisper*	10^{-10}	20
Rustle of leaves*	10^{-11}	10
Barely audible sound	10^{-12}	0

Worked example

Find the sound level in decibels of a sound wave that has an intensity of 3×10^{-8} W/m^2.

(ans. 44.8 dB)

Beats

The alternations of maximum and minimum sound intensity produced by the superposition of two sound waves of slightly different frequencies are called beats.

The number of beats per second is equal to the difference between the frequencies of the two sound waves that are combined.

Doppler Effect

Suppose that a moving sound source emits a sound of frequency f_o.
Let V be the speed of sound, and let the source approach the listener or observer at speed v_s, measured relative to the medium conducting the sound.

Suppose further that the observer is moving toward the source at speed v_o, also measured relative to the medium.

Then the observer will hear a sound of frequency f given by:

$$\boxed{\text{Observed frequency } f = f_o \frac{V + v_o}{V - v_s}}$$

If either the source or observer is moving away from the other, the sign on its speed in the equation must be changed.

Doppler Effect (cont'd)

When the source and observer are approaching each other, more wave crests strike the ear each second than when both are at rest.

This causes the ear to perceive a higher frequency than that emitted by the source.

When the two are receding, the opposite effect occurs – the frequency appears to be lowered.

Worked example

An automobile moving at 30 m/s is approaching a factory whistle that has a frequency of 500 Hz. If the speed of sound in air is 340 m/s, what is the apparent frequency of the whistle as heard of by the driver?

(ans. 544 Hz)

Interference Effects

Self-study – read the appropriate sections in the textbooks.